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Comprehensive 3D Model of Shock Wave-Brain Interactions in Blast-Induced Traumatic Brain Injuries

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14. ABSTRACT This project aims at the development of a realistic and accurate numerical model that can capture the essential physics of shock wave propagation and its interaction with the skull and brain tissue. This information would enable us to address and study the diverse mechanisms damaging the brain to better understand causes and effects during blast-induced traumatic brain injuries. At the present time, a fully 3D numerical model on fixed computational grids for nonlinear acoustic and elastic propagation has been developed and validated against published work and in-house experiments. A realistic modeling domain based on the segmentation and 3D reconstruction of sequential anatomical data obtained from the Visual Human Project is used as input to the computational kernel. Adaptive grid versions of the algorithms by means of wavelet and radial basis functions approaches as well as the inclusion of cavitation effects via effective medium theory and a graphical user interface to the simulation software are currently under development.				
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INTRODUCTION: Blast-induced traumatic brain injury (BI-TBI) is defined as the damaging effect to the brain tissue occurring as a result of a propagating shock wave generated by an explosion. Current TBI models define damage in terms of local brain accelerations versus time. However, blast waves can cause brain damage by other mechanisms including excess pressure (leading to contusions), excess strain (leading to subdural hematomas and/or diffuse axonal injuries), and, in particular, cavitation effects (leading to subcellular damage). This project aims at the development of a realistic and accurate numerical model that can capture the essential physics of shock wave propagation and its interaction with the skull and brain tissue. This information would enable us to address and study the diverse mechanisms damaging the brain to better understand causes and effects during traumatic injuries.

BODY: Efforts in Project Year 1 have been focused on several fronts. Our progress to date is presented below and associated with each task (reported here for reference) in the approved Statement of Work .

Task 1: *this task includes the theoretical and numerical development of an acoustic and elastic model to simulate the interaction of a shock wave with the human skull and brain. Both acoustic and elastic wave propagation components of the model are based on a system of first order partial differential equations (PDEs). The acoustic model includes continuity of mass, continuity of momentum, and a Taylor's series representation of the isentropic equation of state which links density and pressure fluctuations and provides the source for the quadratic nonlinearity. Tissue specific frequency power-law absorption is included via N independent relaxation mechanisms where the necessary relaxation times and moduli are found by applying a nonlinear least square procedure. The elastic model will be developed in terms of coupled isotropic stress-velocity PDEs where viscoelastic processes will be incorporated via N relaxation mechanisms. Constitutive stress-strain relationships will be based on published work. During this task, the computational kernel for both the pseudospectral method and the wavelet time domain method for adaptive grid refinement based on collocation points will be developed. Specifically, fast and robust procedures will be developed for the generation of realistic 3D computational domains for skull and brain; for the computation of spatial derivatives and accurate multi step time integrators; for the generation of multi-level grid adaptivity to dynamically track the significant features of the solution; and for the implementation of perfectly matching layers boundary conditions to avoid spurious reflections from the computational boundaries. All subroutines will be developed for both sequential and parallel processing on scalable single or multiprocessors computer clusters. Parallel implementation will be based on domain decomposition methods using the Message Passing Interface protocol.*

Progress to date: We have fully developed the theoretical model for both acoustic and elastic interactions in heterogeneous media as coupled systems of first order partial differential equations. The model, shown in Figure 1, is capable of full wave, acoustic and elastic propagation in lossy biological tissue. It accounts for the major physical mechanisms that take place during the interaction of shock waves with tissue and includes acoustic nonlinear effects to sustain and propagate the shock wave, the generation of both compressional (P) and shear (S) waves, and effects from diffraction, multiple reflections, scattering, and frequency dependent power-law of absorption which is characteristic of biological media.

Based on the theoretical model we have also fully developed the numerical kernels for nonlinear acoustics and elastic wave propagation in two-dimensional (2D and 2.5D (cylindrical symmetry)) and fully three-dimensional (3D) domains. In this respect, we have developed, implemented, and debugged source code in Fortran 90/95 for all the necessary subroutines to perform the FFT-based pseudospectral time domain method. The computational numerical kernels have been developed in both sequential and parallel fashion via the message passing interfaces (MPI) methods and domain decomposition techniques. We used the OpenMPI version of MPI, which is a portable, fully supported, and freely available implementation of the MPI standard for message passing libraries (<http://www.open-mpi.org/>). In particular we developed algorithms for: 1) accurate pseudospectral first- and second-order spatial derivatives in 2D, 2.5D, and 3D domains based on spatially staggered grid. Spatially staggered grid have been shown to greatly reduce spurious Fourier oscillations and Gibbs phenomena at transition boundaries in heterogeneous materials, thus increasing the accuracy and stability of the method; 2) a time staggered fourth-order Adam-Bashforth method for time integration. This is an explicit multistep time integration algorithm with increased stability domain and accuracy, thus drastically reducing dispersion effects for a given time step compared to standard methods. It also allows the use of larger time steps in the integration procedure and therefore provides faster convergence to the solution; 3) the implementation of the perfectly matched layers (PML) boundary conditions. PML allow the acoustic/elastic wave to exit the computational domain without numerical spurious reflections at the boundaries and therefore greatly aid in reducing the overall size of the computational domain and the total number of computations without corrupting the solution with non-physical signals.

We have additionally developed a numerical kernel based on a wavelet-based time domain method (WTDM) for dynamic grid adaptation in 2D and 2.5D domains. To this extent, we have implemented subroutines for: 1) the 2D (forward and inverse) Fast Lifted Interpolating Wavelet Transform (LIWT). The single-level fast 2D LIWT is based on the use of the lifting scheme applied to second-generation wavelets and is implemented in order N operations (where N is the number of collocation points transformed) through the use of sequential interpolating filter banks in a tensor product approach. M -levels transforms are obtained by the recursive application of the single-level transform; 2) interpolation and spatial partial derivatives routines based on cubic splines on staggered grids where pressure and velocity components exist on different, interlaced spatial and temporal grids; 3) a multi-level grid generation routine based on the wavelets coefficients of the LIWT to dynamically track the significant features of the solution. The grid generation uses search algorithms together with a thin-plate splines approach to interpolate scattered data and generate the adaptive, updated computational grid at successive time step as the waves propagates. An efficient dynamic grid solution will significantly increase the accuracy of the solution while drastically reducing both the computational time and resources necessary for the model.

In this regard, we also started investigating the use of fast radial basis functions (RBFs) as an alternative kernel to fast Fourier (FFTs) and wavelet based computations for adaptive grid modeling. The RBFs provide the advantage of performing computations on unstructured and scattered grids and therefore allow better handling of curved interfaces in the adaptive grid framework in comparison with the dyadic grid refinement and the structured, regular grids required by the wavelet and FFTs approaches respectively. The drawback of using RBFs, however, lays in the lack of very fast algorithms for non-diagonal dense matrix inversion which are comparable with the $N\log N$ operations for the FFT and the ill-conditioned and close-to-singular nature of these dense matrices. We are currently experimenting with several approaches to resolve these drawbacks, from recursive block-decomposition for fast matrix inversion to several preconditioning methods to reduce singularity. We are also experimenting with the fast multipole method, a relatively new approach to dense, singular matrix inversion which has shown promise in being able to achieve good accuracy in close to order $N\log N$ computations. We will thoroughly study this new approach in the coming months to assess its performance in terms of computational speed and accuracy compared with the previous methods.

For the generation of a realistic modeling data for TBI modeling we used anatomical image slices from the Visual Human Project. We segmented, rendered, and reconstructed in 3D the head section of the human man. Each slice is segmented according to the different anatomical structures present and each pixel belonging to a given structure is integer-coded (color) in the database. All the slices are then stacked together to provide a full 3D reconstruction where different integers labels correspond to different tissues/organs. Figure 2 shows our results to date. We have the ability to select subsections of this database and perform computations only in the region of interest. We are currently developing subroutines to load this model into our main computation kernel and translate the integer-coded tissues to properly assign acoustic and elastic material parameters. Furthermore, we are also in the process of developing accurate and robust interpolation routines to increase the resolution of the 3D head dataset to a level necessary for the stability and accuracy of the numerical calculations during shock wave propagation.

Task 2: *this task incorporates the effects of wave propagation in a bubbly fluid into the model. It includes the necessary refinements of the system of equations that describe an effective medium within the numerical framework implement in Task 1. As a shock wave propagates through a liquid, it is followed by a rarefaction. If the magnitude of this negative pressure fluctuation exceeds the cavitation threshold, then bubbles will spontaneously nucleate. The effects of the bubbles on subsequent shock wave propagation will be included, and the physiological effects associated with violent collapse of the bubbles will be considered. Effective medium theory for wave propagation in a bubbly liquid is based on the reduction of the two phase media (ie., gas bubbles and fluid) to an effective medium with frequency dependent dispersion and attenuation. The collection of bubbles in the presence of a sound field essentially act to modify the bulk compressibility and density of the fluid to produce a frequency-dependent, complex, bulk compressibility and a reduced density. Effective medium parameters change dynamically during the computations based on the bubble sizes and distributions per unit volume (the void fraction).*

Progress to date: Towards the inclusion of cavitating bubbles due to the shock front, we have successfully developed an analytical representation of the effective medium theory for the different media present in the human head and have determined the necessary effective wave numbers. Effective medium (EM) models replace a complex environment for wave propagation by an effective homogeneous medium. For a distribution of bubbles in a fluid, an EM model reduces the multiple scattering of an acoustic field to an estimate of the complex wavenumber, k_e . For a fluid with density, sound speed, viscosity, and surface tension denoted by ρ , c , μ , and σ , an EM model is given by the following set of equations.

$$k_e^2 = k^2 + 4\pi\omega^2 \int_0^\infty \frac{a n(a) da}{\omega_0^2 - \omega^2 + i(b_v + b_t + b_a)},$$

$$\omega_0^2 = [p_0 \Re(\Phi) - 2\sigma/a] / \rho a^2,$$

$$b_v = 4\mu\omega / \rho a^2, \quad b_t = p_0 \Im(\Phi) / \rho a^2, \quad b_a = \omega^2 ka$$

where a is a characteristic radius of the bubble size distribution $n(a)$, ω_0 is the resonance frequency for a bubble with radius a , and b_v , b_t , and b_a are viscous, thermal, and scattering losses. The ambient pressure is p_0 , Φ is determined from the thermal properties of the gas, $k = \omega/c$ is the wavenumber in the fluid without bubbles. To account for all orders of multiple scattering, the scattering loss can be replaced by $b_a = \omega^2 k_e a$. For more details on the derivation of the effective medium theory please refer to [1-3].

In this task, we are encountering significant issues in the integration of the effective medium wave numbers for the head materials into the framework of the relaxation mechanisms approach for the governing equations. At present, our least square fit approach for just two relaxation mechanisms, is not sufficient to maintain causality and accuracy in the attenuation and sound speed for the nonlinear wave propagation which results in the solution either showing unphysical behavior or even growing unstable over time. We are currently investigating these issues thoroughly including the use of more than two relaxation mechanisms, which, unfortunately, will result in an increase in the computational load and complexity of the model.

Task 3: *this task includes a preliminary validation of the numerical model against available and published benchmark solutions of reduced shock wave propagation models (such as the Burgers Equation or the KZK model) and elastic models. Validation can also be achieved by comparison with available experimental data from extracorporeal shock-wave lithotripsy. Task 3 is expected to span a time period of about nine months in that any incremental change to the mathematical and numerical model needs to be revalidated.*

Progress to date: We have validated the pseudospectral and WTDM numerical implementation of the individual sequential and parallel subroutines for spatial derivatives and integration against an array of analytical solutions for different functional forms and have obtained an excellent level of accuracy which, as expected, scales very well with the number of points used in the calculations. We have also validated the full sequential and parallel implementation of the acoustic and elastic wave model based on pseudospectral methods against benchmark analytical solutions for simple geometries and against results from other published work. Again, our model is in very good agreement with these results. Additionally, we also validated the nonlinear acoustic propagation model against experimental data available in our laboratory through other projects. A sample result showing excellent agreement between experiment and simulations for different levels of shocks is presented in Figure 3.

Task 4: *this task involves the development of a graphical user interface (GUI) to the numerical kernel to simplify the user interaction and visualization of the computed results. The software GUI will use the Fast Light Toolkit (FLTK). FLTK is a widgets-based, cross-platform C++ GUI toolkit which provides modern GUI functionality and it is designed to be small and modular enough to be statically linked to other applications.*

Progress to Date: During this reporting period we have not commenced work on this task.

KEY RESEARCH ACCOMPLISHMENTS:

- We have fully developed sequential and parallel kernel versions of a fully 3D model for both acoustic and elastic wave propagation on fixed computational grids based on the pseudospectral time domain method.
- We have developed 2D sequential kernels for acoustic wave propagation based on the wavelet time domain method which include adaptive grid refinement.
- We have successfully developed the analytical representation of the effective medium theory for the different media present in the human head and determined the necessary effective wave numbers.
- We have validated both the sequential and parallel implementations of the acoustic and elastic wave propagation kernels based on pseudospectral methods against other published work.
- We have validated the nonlinear acoustic propagation model against experimental data available in our laboratory through other projects.
- We have completed segmentation, labeling, and reconstruction of the head region of the Visual Human Project man.

REPORTABLE OUTCOMES:

Poster presentation: “Comprehensive Three Dimensional Model of Shock Wave-Brain Interactions in Blast Induced Traumatic Brain Injury”, Department of Defense Third Military Health Research Forum, Hallmark Crown Center, Kansas City, Missouri, August 31 – September 3, 2009

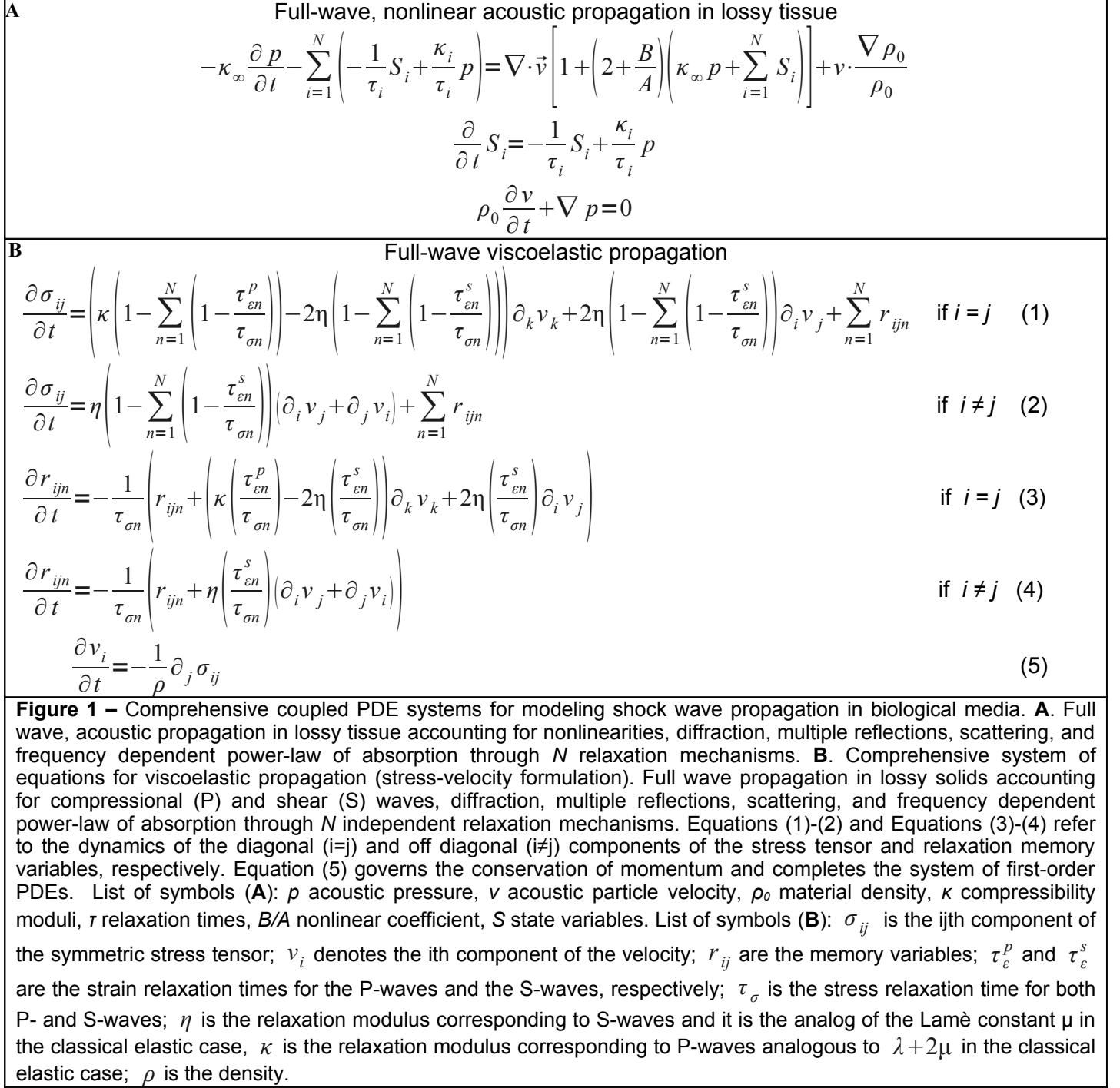
CONCLUSION: We have developed and validated a fully 3D acoustic and elastic wave propagation model to investigate the effects of blast-induced shock waves to the head and brain regions. The modeling domain is based on the segmentation, labeling, and 3D reconstruction of real anatomical slices from the Visual Human Project. Inclusion of cavitating bubble effects, extension of the numerical algorithms to adaptive grid refinement during the calculations, and the addition of a graphical user interface to the software are currently in progress and under development.

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- [3] K Commander, LA Crum, and A Prosperetti, “Nonlinear bubble dynamics,” *J. Acoust. Soc. Am.*, **83**, 502 – 514 (1988).

APPENDICES:

SUPPORTING DATA:



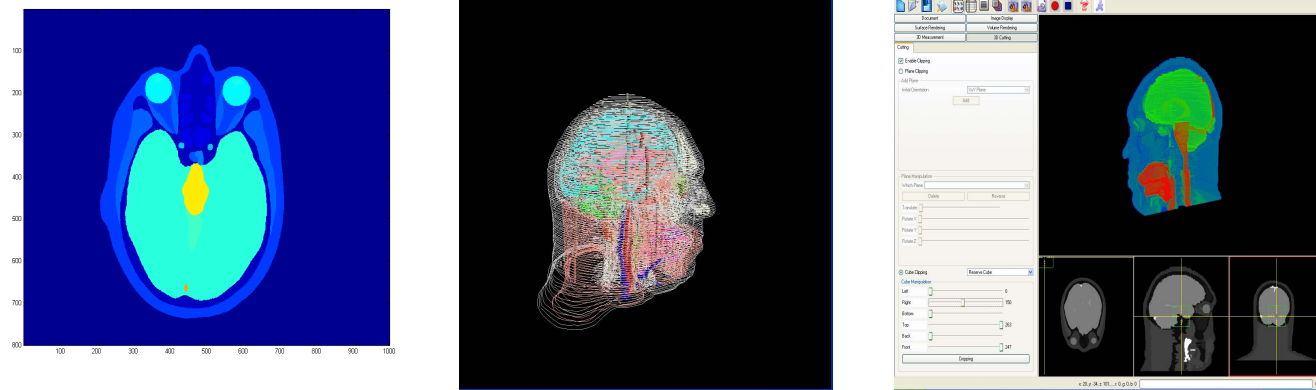


Figure 2. 3D segmentation and reconstruction of the head region of the Visual Human Project (VHP). **Left:** Segmentation and color-coded fill of the major tissue/structures in the original anatomical slice of the VHP as provided by the NIH database. **Center:** 3D contours stack of all the segmented slices. **Right:** Full 3D rendering of the head section showing the different structures and the ability to chose the intersecting planes of the interested volume.

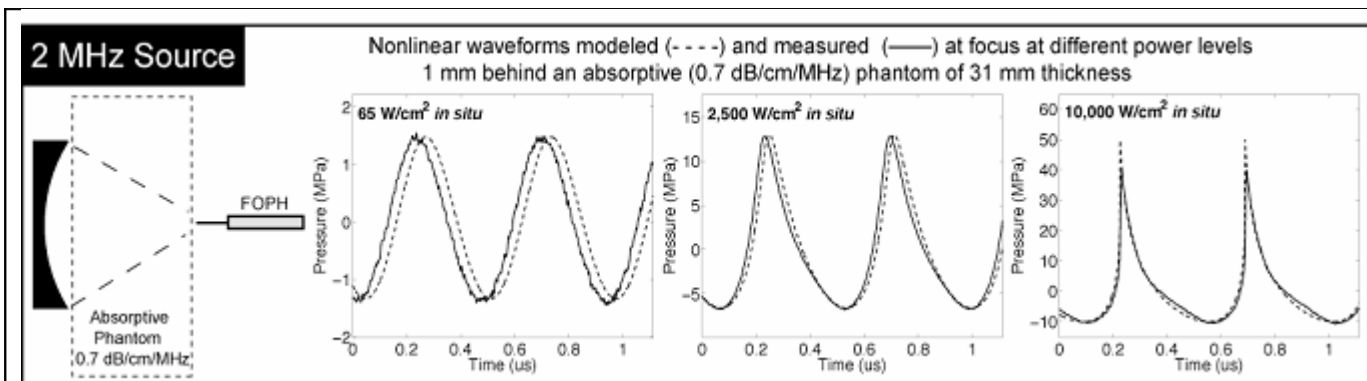


Figure 3. Validation of the acoustic modeling *versus* experiment in absorptive phantom. Nonlinear waveforms with shocks were measured and modeled at focus in less than 0.5 mm beyond a phantom of 31 mm thickness and found in excellent agreement.